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Final Report

IMAGE SENSOR DATA BASE FOR THE DARPA ALV PROGRAM

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This report describes the acquisition of imaging sensor data for the DARPA Autonomous Land Vehicle (ALV) Program. Data were acquired during four seasonal measurement periods from September 1984 through June 1986 at the Martin Marietta ALV Test Site near Denver Colorado. Passive Multispectral, 3-D Imaging, and color TV sensors were installed on an instrumented van and operated over road networks and various fixed locations at the Martin site. The report presents the specifications for the sensors and describes each measurement period including site locations on map overlays. Data format for the sensors is described and field logs are included as appendices.

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SECTION I
INTRODUCTION

1.1 Background

The Environmental Research Institute of Michigan (ERIM) was awarded a contract in July 1984 to provide 3D sensor support and data base for the DARPA Autonomous Land Vehicle (ALV) program. This program also provided for delivery of a follow-on "Vision" sensor which would provide cross-country autonomous navigation capability via multispectral reflectance data on terrain or objects in front of the vehicle. The sensor, which is scheduled for integration into the ALV in 1987, has active spectral bands selected on the basis of models and from measured data from downward-looking sensors, i.e., satellite and aircraft data. A multispectral data base was therefore required not only to verify the proper band selection, but also for developing algorithms applicable to processing the multispectral data, classifying the terrain and navigating the vehicle.

ERIM proposed acquiring "Psuedo-Active" multispectral data via modifying a passive airborne scanning system, installing it in an instrumented van and acquiring the data at the Martin Marietta ALV test site near Denver Colorado. The simulated active data would be obtained by operating the sensor at selected times, i.e., early morning or late evening, when the instrument could be positioned to achieve small bistatic angles with the sun positioned behind the sensor. See Figure 1-1.

1.2 Plan for The Program

The original ALV contract provided for acquisition of 3D sensor data at the Martin-Denver test site. This program was implemented in September 1984 utilizing the 3D sensor originally delivered to Ohio State University (OSU) for use on their adaptive suspension vehicle (ASV).[1,2] The plan was to integrate the passive multispectral

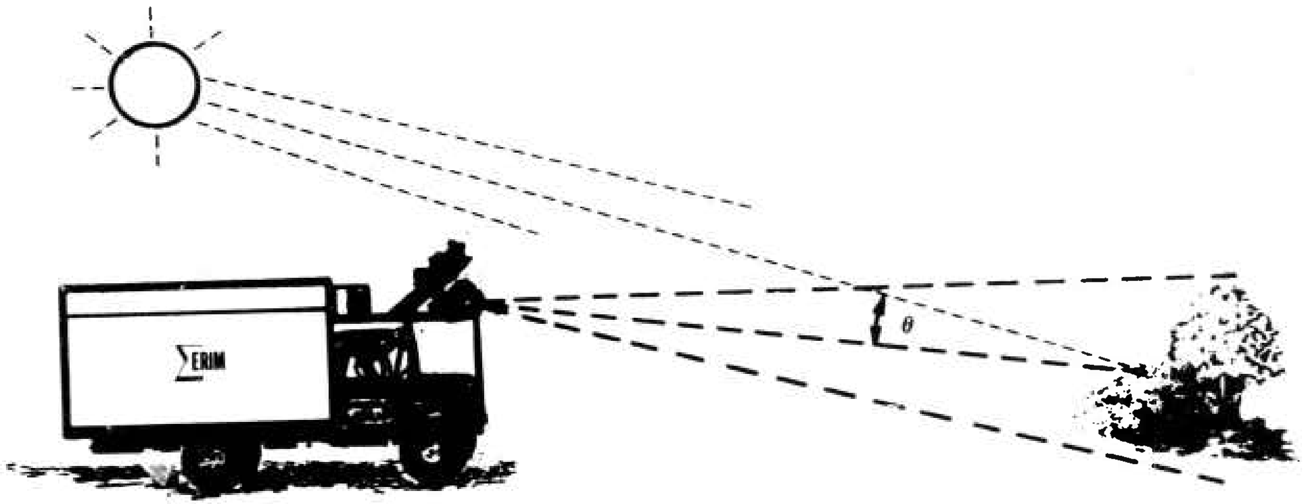

Figure 1-1. Sensor-Solar Geometry for Psuedo-Active Data
(θ = Small Bistatic Angle)

measurements with additional 3D sensor measurements at the Denver site. A schedule was adopted providing for three data acquisition periods coinciding with the Spring, Summer and Fall vegetation growth seasons. The first measurement period was scheduled for July 1985 with follow-on measurements during September 1985 and May 1986.* Although winter data were desirable, measurements were not considered feasible due to the uncertain weather conditions and the trafficability of the terrain at the Martin site during the winter months. The July 1985 measurements were coordinated with the U.S. Army Engineering Topographic Laboratories who made spectral reflectance measurements and acquired extensive ground photography during the period.[3]

This report describes the sensors used on the measurement programs, summarizes the data acquired during the measurement periods at the Martin-Denver ALV test site and discusses the data reformatting and distribution to the ALV vision contractors.

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* The original DARPA/TACOM Contract (DAAE07-84-K-R003) provided for two sets of measurements with the 3D sensor at the Martin-Denver test site and a separate contract (DAAE07-86-C-R019) was negotiated for two additional measurement periods with the passive Multispectral Sensor (MSS). The MSS was, in fact, employed for the latter three measurement periods and a discussion of all measurements, i.e., four periods is included in this report for completeness.

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SECTION 2
INSTRUMENTATION

The imaging sensors were installed on ERIM's instrumented van in a configuration similar to that shown in Figures 2-1 and 2-2. The van currently has self-sufficient power generators installed; however, during the first two measurement periods, instrument power was obtained from a power cart towed behind the vehicle. Arrangements were made by Martin Marietta for loan of the power cart from the Air National Guard in Denver. Arrangements could not be made with the guard for the September 1985 measurements, however, and hence ERIM purchased and installed new prime power (115 VAC, 60 Hz) and secondary power (115 VAC, 400 Hz and 28 VDC) for the May 1986 measurement period.

Sensor data is recorded in the van on 14-track high-density digital tape. The recorders are designed primarily for airborne operations and hence the requirement for 400 Hz and 28 VDC power. The recorders and all control instrumentation are installed in vertical racks in the interior of the van.

A color TV system (Figure 2-2) is bore-sighted with the 3D and Multispectral sensors. TV data is recorded on analog tape (3/4-in. U-Matic VCR). A wide-angle lens (FL=8 mm) is used on the camera providing a field of view approximately equal to that of the scanning sensors.

2.1 ASV Sensor

As indicated in Section I, the ASV Sensor provided to Ohio State University was utilized for the initial set of measurements at the Denver test site. This sensor was the initial 3D imaging sensor fabricated by ERIM for the DARPA program and has operating parameters somewhat different than the ALV sensor used for the later measurements.

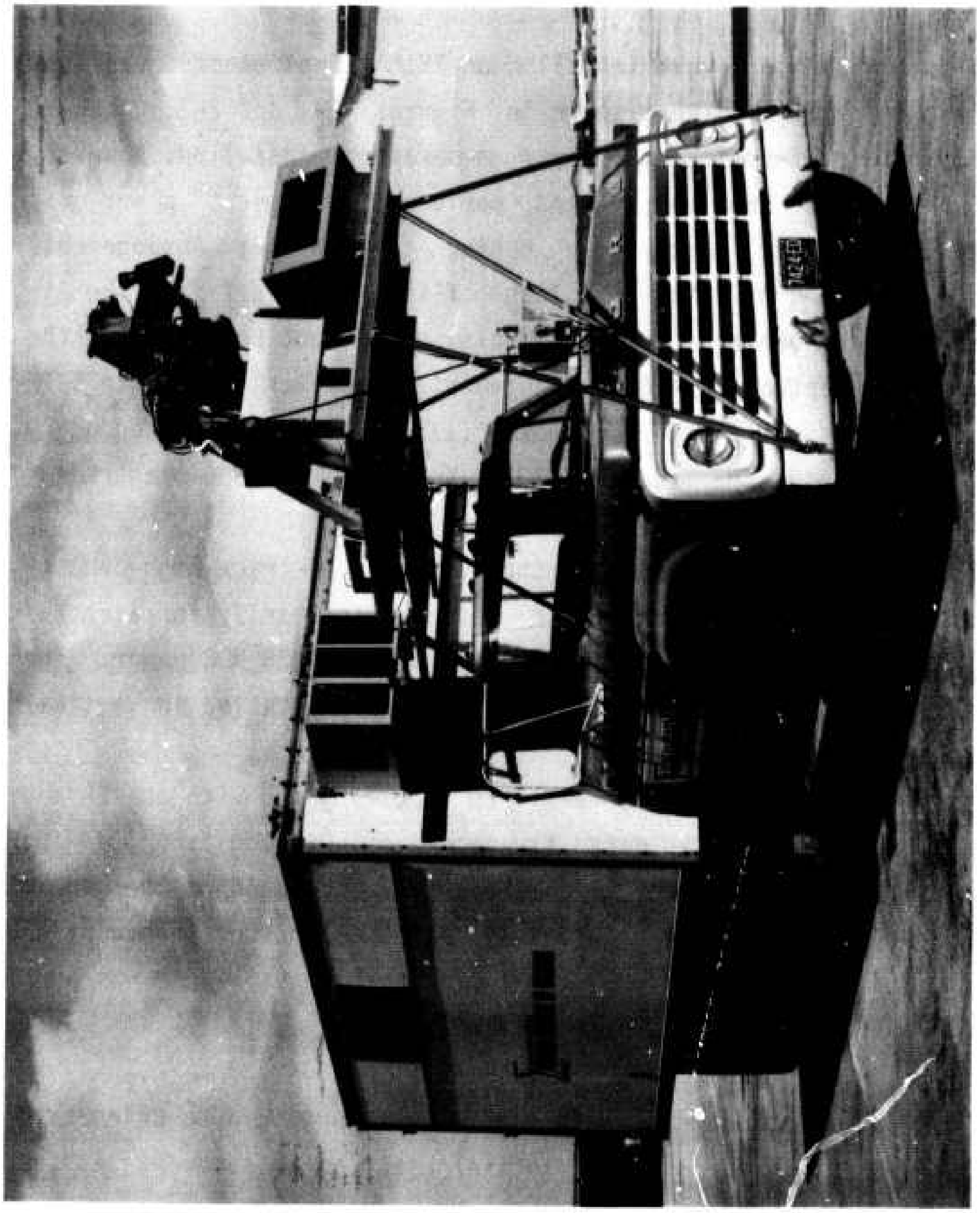

Figure 2-1. ERIM'S Instrumented Van

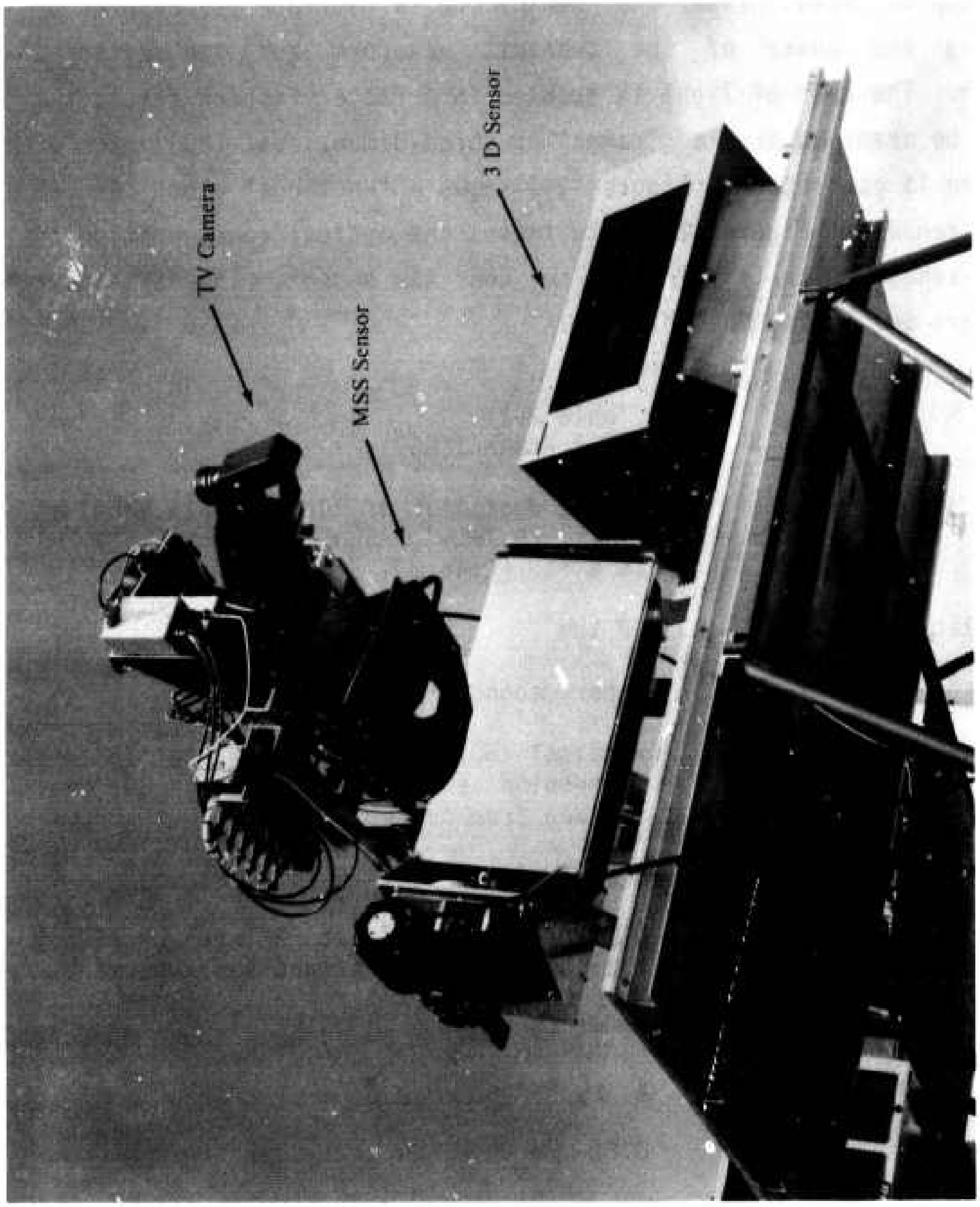

Figure 2-2. 3D and MS Sensors on Instrument Platform

The principle of operation of the two sensors is the same. Radiation from a laser diode, emitting at 0.82 micrometers, is modulated by a sinusoid waveform. The transit time required for the light beam to travel from the sensor to a surface is measured by comparing the phase of the transmit waveform and the reflected waveform. The beam of light is scanned in a raster fashion across the area to be examined and a "range" or three-dimensional (3D) image of the scene is generated. Figure 2-3 shows a functional block diagram of a 3D sensor. Figure 2-4 illustrates the optical configuration of the ALV sensor which is similar to the ASV sensor. The ASV sensor parameters are listed in Table 2-1.

Table 2-1
ASV SENSOR PARAMETERS

IFOV:	1 deg; footprint of 0.5 ft. (15.2 cm) at 32 ft. [9.75 m], and 0.14 ft. [4.27 cm] at 8 ft. [2.44 m]
Sample Rate:	92 kHz
Frame Rate:	2 per second
Scan Range:	Vertical 60 deg, 15 deg to 75 deg depression angle; horizontal 80 deg, ±40 deg from center line
Range Resolution:	8 bits, 1 bit = 0.125 ft [3.81 cm]
Range Noise:	0.2 ft [6.10 cm] at 32 ft [9.75 cm] reflectance = 10%, bright sunlight
Ambiguity Interval:	32 ft (9.7 m)
Scanner Output Format:	θ, ϕ , Range
Wavelength:	0.82 µm
Volume:	2 ft^3 [0.566 m^3]
Weight:	85 lb.
Power:	480 W, 24v DC

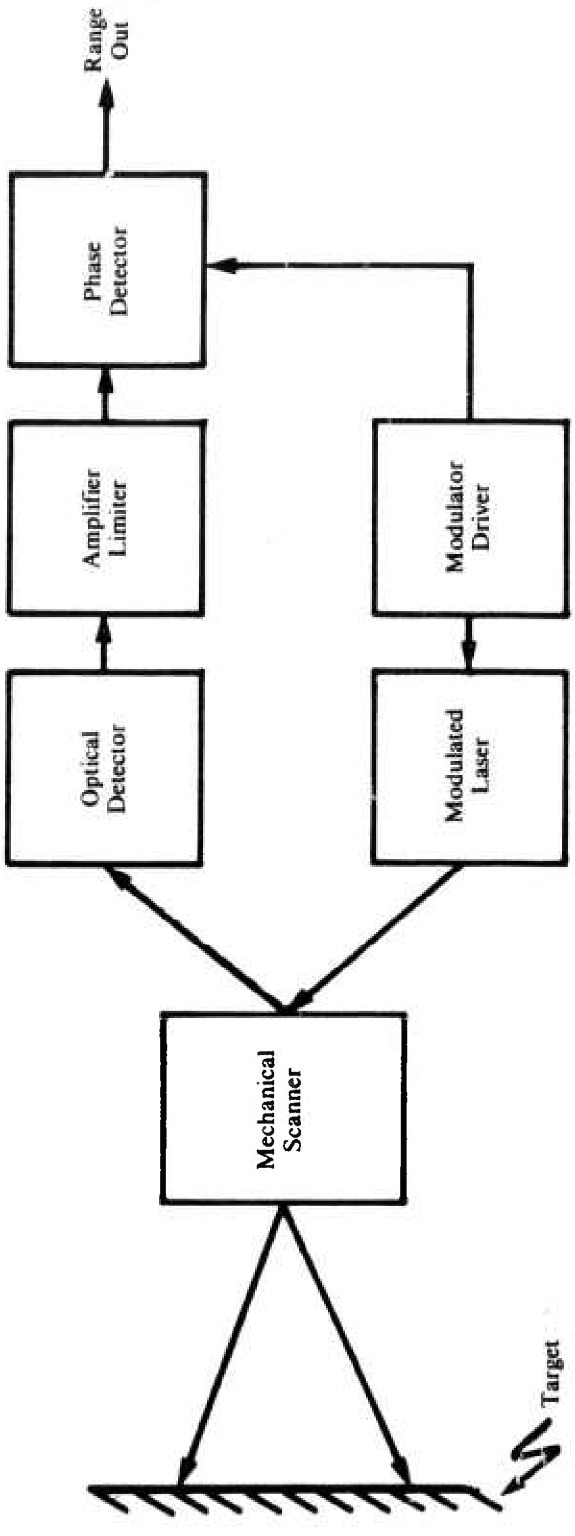

Figure 2-3. Block Diagram of 3D Sensor

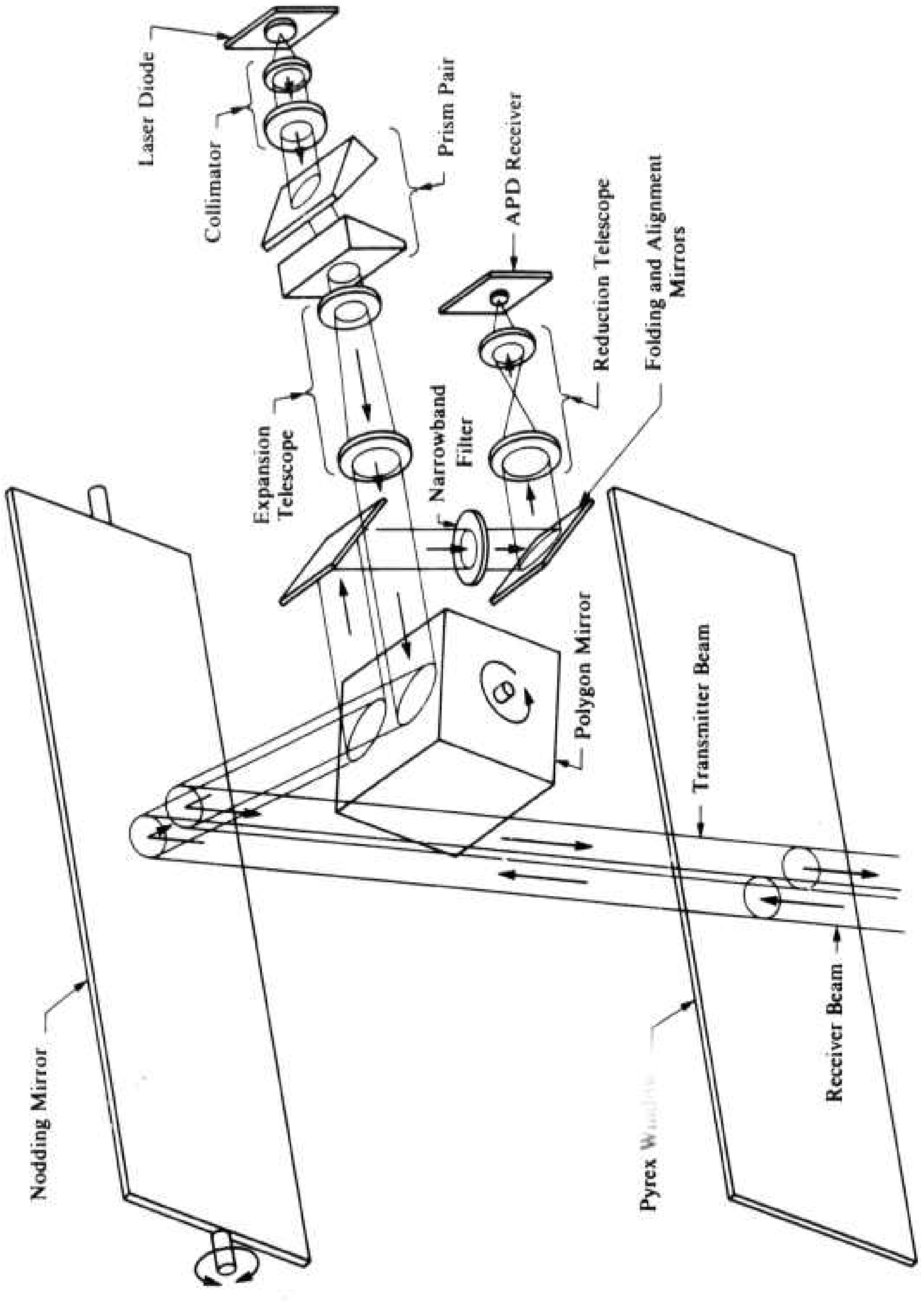

Figure 2-4. ALV Optical System

2.2 ALV Sensor

The ALV sensor is a second generation 3D sensor, four of which were built by ERIM. ERIM retains one; two were delivered to DARPA ALV contractors, Martin-Marietta and Carnegie-Mellon University and the fourth was delivered to a government agency. The Martin sensor is currently installed on the Autonomous Land Vehicle.

The operating principle of the ALV sensor is the same as the ASV sensor (Section 2-1); however, several specifications have been changed. Table 2-2 lists the ALV sensor parameters.

TABLE 2-2
ALV SENSOR PARAMETERS

TFOV	
Horizontal	80°
Vertical	30°
IFOV	0.5°
Beam Size	0.44 ft. (at 50 ft.)
Horizontal Pixels	256
Vertical Lines	64
Ambiguity Interval	64 ft.
Frame Rate	2 Hz
Data Rate	92160 Hz
Laser Power	100 MW
Wavelength	0.82 μm
Range Noise	0.4 ft. (at 50 ft, 10% refl.)
Output Signal	analog-Logarithmic
Sensor Dimensions	
Height	14 in.
Width	29 in.
Depth	22 in.
Weight	85 lbs.
Power	24 VDC, 450 W

2.3 Multispectral Sensor

The Multispectral Sensor (MSS) was designed in the early 1970's by the Bendix Corporation as a downward-looking, passive airborne device. The system is a line scan instrument whereby the second dimension of an image is normally generated by the forward motion of an aircraft. Solar radiation reflected from terrain is collected and focused on the entrance aperture of a spectrometer which divides the spectrum into ten bands ranging in wavelength from 0.38 μm to 1.06 μm. An additional band to image thermal radiation, i.e., emitted radiation (8-14μm) is also available by using a dichroic beamsplitter to separate the long wavelength portion of the spectrum. The optical configuration for the sensor is illustrated in Figure 2-5.

ERIM modified the airborne system for installation on its van in a forward-looking mode. The modification was accomplished by placing a nodding mirror beneath the sensor scan aperture to generate a vertical scan, thereby providing a two-dimensional image. A second major modification was removing the thermal detector and replacing it with a unique 3-element detector which provided data in the short wave infrared (SWIR) portion of the spectrum. These bands were desired to provide additional data relating to soil type, soil moisture and vegetative cover. Table 2-3 lists the spectral bands for which the sensor was reconfigured.

TABLE 2-3

SPECTRAL BANDS FOR THE MULTISPECTRAL SENSOR

CHANNEL (Band)	WAVELENGTH (Micrometers)	CHANNEL (Band)	WAVELENGTH (Micrometers)
1	0.44 - 0.49	7	0.70 - .74
2	.49 - .54	8	.77 - .86
3	.54 - .58	9	.97 - 1.06
4	.58 - .62	10	1.04 - 1.4
5	.62 - .66	11	1.5 - 1.8
6	.66 - .70	12	2.0 - 2.6

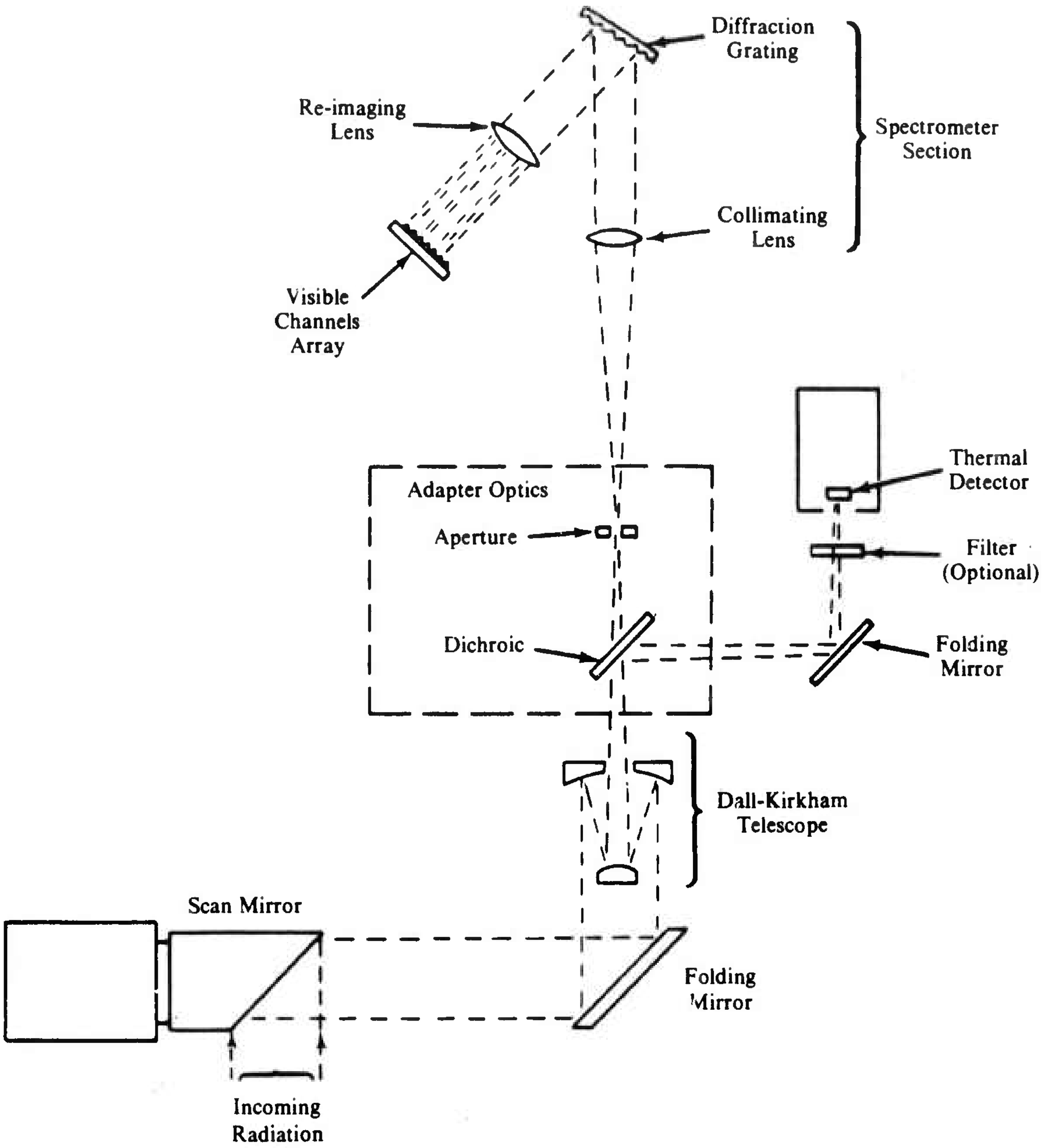

Figure 2-5. Optical Configuration for the Multi Spectral Sensor

The modified sensor utilized the existing dichroic mirror to reflect the SWIR radiation onto the three element detector. This provided a minimum 20 percent reflection at 1.0 μm and approximately 64 percent reflection at 2.6 μm. See Figure 2-6. The detector chips each have a narrow band interference filter mounted inside the detector dewar to restrict the radiation to the given bands.

2.4 Ancillary Instrumentation

Ancillary instrumentation included a Litton LTN-51 inertial navigation system (INS). This unit was mounted on the same platform as the sensor heads and outputed three-axis acceleration data. The data are integrated into the "header" information recorded on digital tape with each scan line from the 3D sensor. This information may be used to correct image distortions caused by the roll or pitch of the vehicle.

Other instrumentation included a time code generator, the output of which was recorded on an audio track of the VCR used for recording the color TV.

2.5 Calibration Panels

ERIM provided calibration panels, 4-ft. square, for placement in various scenes as reflectance control points. Four panels were prepared with special reflective paints; however, usually only two panels were used during the measurements. Four-inch square samples were also prepared and run on ERIM's spectrometer for calibration purposes. Spectral reflectance curves for the painted panels are shown in Figure 2-7.

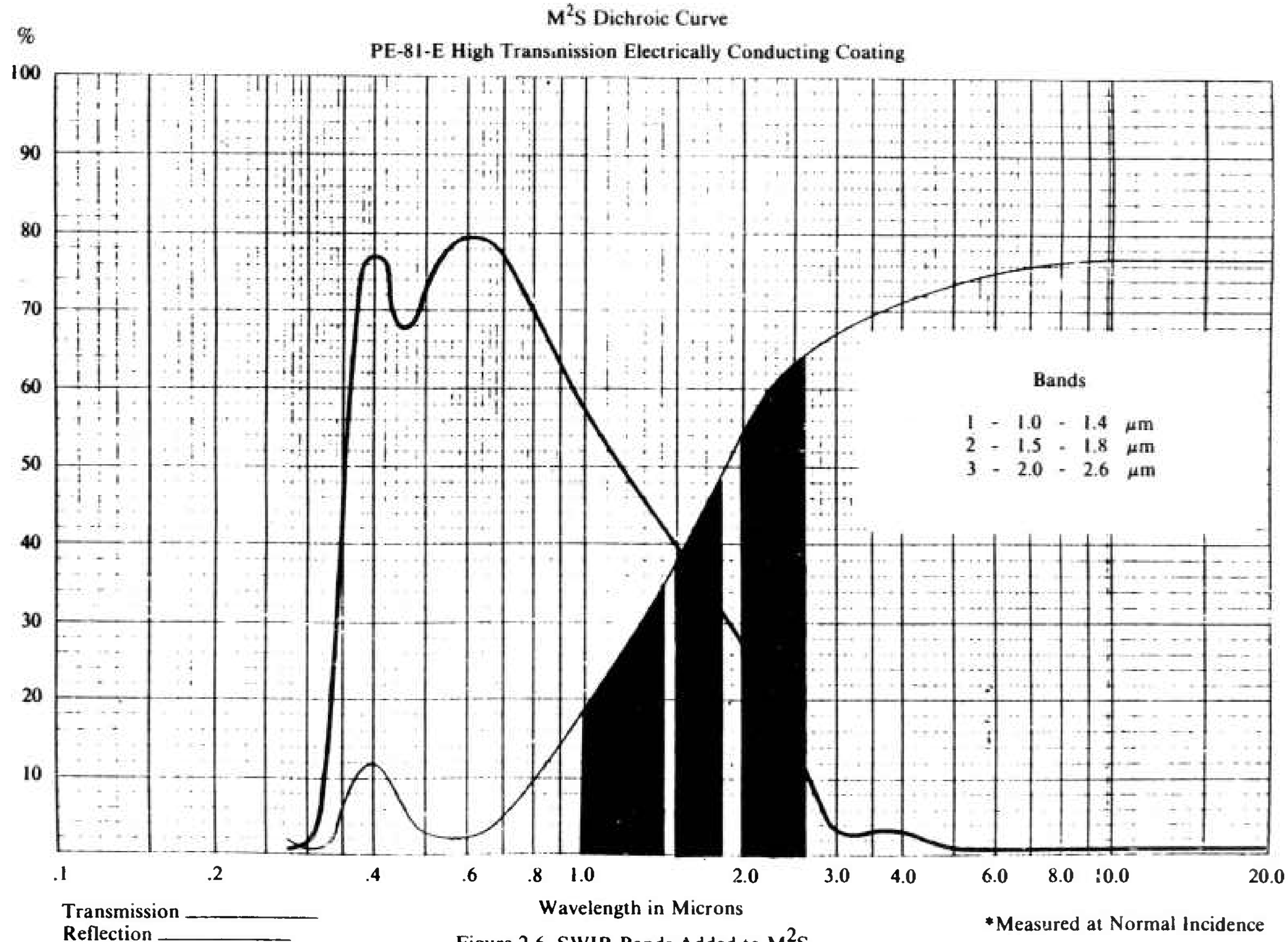

Figure 2-6. SWIR Bands Added to M^2S

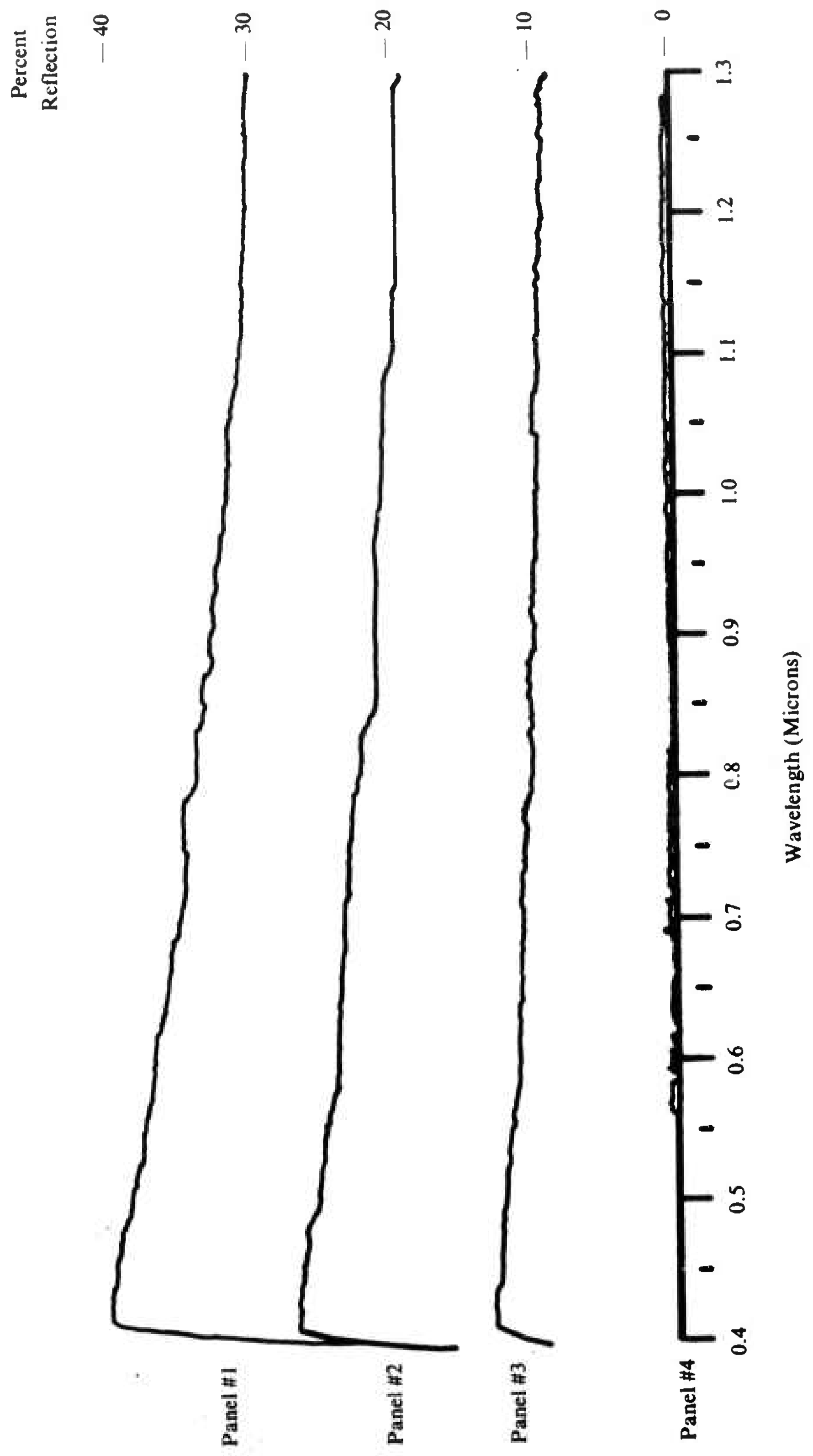

Figure 2-7. Spectral Reflectance of Calibration Panels

SECTION 3
DATA ACQUISITION - AL/ TEST SITE

ERIM acquired sensor data on four different occasions at the Martin-Denver ALV test site:

1) September 1984
2) June 1985
3) September 1985
4) May 1986

ERIM's instrumented van was on site for approximately five days for each mission.

An aerial photograph of the Martin Marietta Denver Complex is shown in Figure 3-1. Map overlays shown in subsequent sections indicate the areas where the various measurements were made. Appendix's A through D contain the data collection logs provided by ERIM's field engineer for each measurement period.

3.1 September 1984 Measurements

The September 1984 measurements were an initial attempt to obtain 3D sensor data over the ALV road following course at the Denver test site. The only sensor available at the time was the ASV-84, a 3D sensor fabricated by ERIM for use on the Adaptive Suspension Vehicle being constructed at Ohio State University (OSU). Arrangements were made with DARPA and OSU to use the sensor for the initial measurements on the ALV program.

The September 1984 measurements went exceedingly well considering it was the initial period and many logistics had to be worked out with the site contractor, Martin Marietta. Martin made the necessary arrangements for loan of a power cart from the Air National Guard. ERIM's van was housed in the ALV garage when not actually making measurements. The test plan provided for 3D data collection over road areas designated for the 1985 and 1986 ALV road-following demonstrations. The sensors were operated over all paved roads

Figure 3-1. Aerial Photograph of the Martin Marietta Denver Complex

selected for the scenarios; a few dirt roads were also traversed. See Figure 3-2. Data was gathered at speeds ranging from 5 to 10 miles per hour. Note, the DARPA/Martin test plan for the ALV called for demonstrations during 1985 of both 5 and 10 km/hr. The van was driven both on road centerline and the right hand lane in order to get representative data. Some data was acquired with the van weaving from side to side.

3.2 July 1985 Measurements

The test plan for the July 1985 measurements was designed to acquire both 3D road following data and MSS data of "typical scenes". Four days were spent on site; the first day was devoted to sensor installation and check-out. The ALV road networks, both paved and cross country, were run on Day-2 utilizing the 3D sensor and TV. Traverses were made in both directions over the roadways. The 3D sensor was set to nominally scan an area from -1° to -31° below the horizon. Additional data was also acquired at a depression angle of -16° to -46° at the request of Martin who wanted to analize data close in to the vehicle.

The MSS data cannot be acquired with the van moving since it takes approximately 10 seconds to acquire a frame of data and movement would cause unacceptable distortions in an image. Sites were selected such that the sun would be behind the van. Measurements were made usually in a sequence of 4 or 5 frames (positions) at each location. The initial frame would be taken and then the van with sensors moved ahead 30-50 feet and the process repeated. The 3D sensor and TV system were also operated simultaneously with the MSS. Seven locations were imaged in two days of operation, resulting in 42 runs of MSS data. It was not possible to operate during evening hours due to cloud build-up over the site. As can be seen from the data logs in Appendix B, morning data acquisition was performed from approximately 06:30 until 09:30. Figure 3-3 indicates the locations of the road networks and the selected MSS sites over which data was taken.

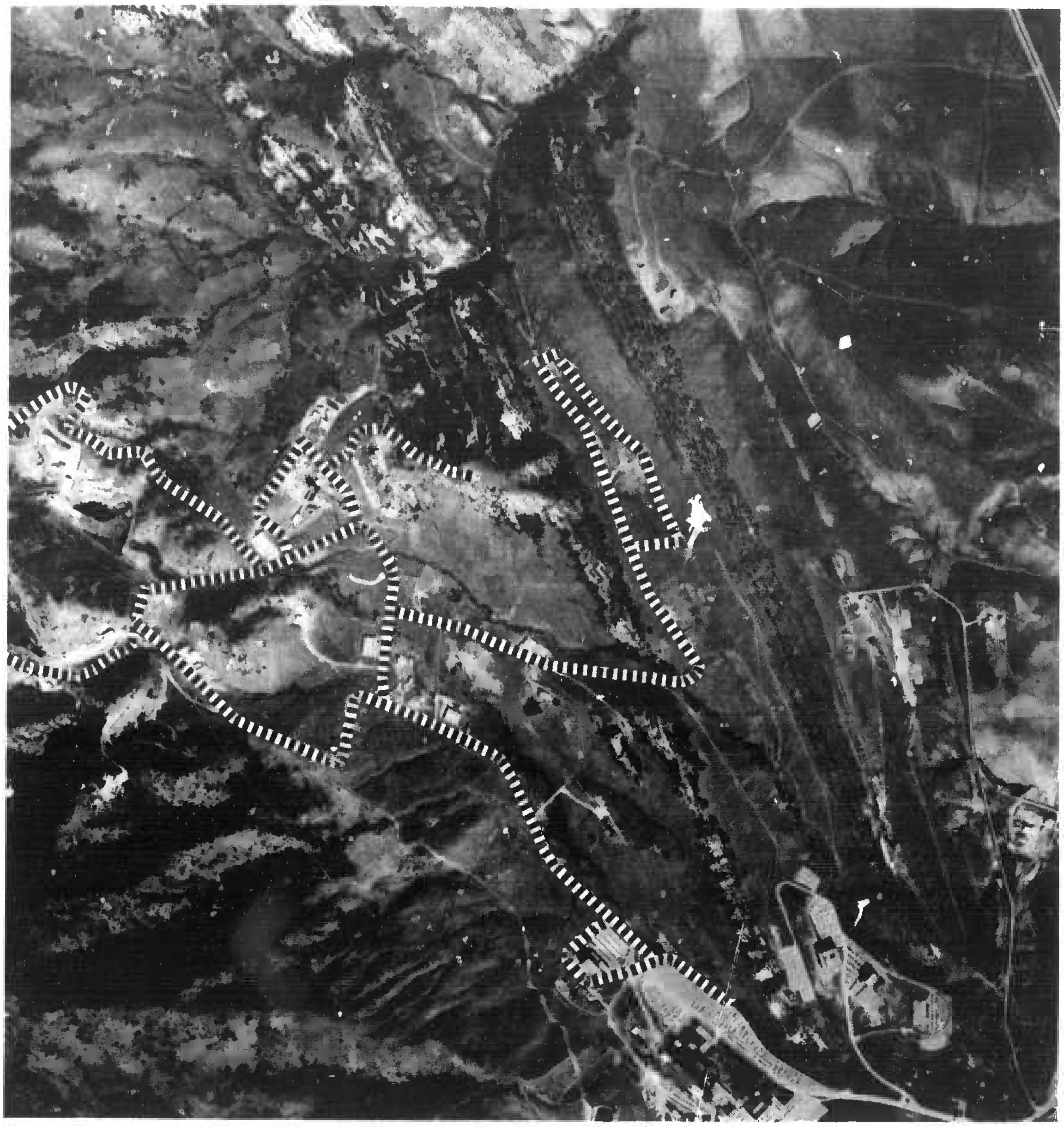

Figure 3-2. Measurement Test Sites—September 1984

▮▮▮▮▮▮ Indicates Road Areas Traversed

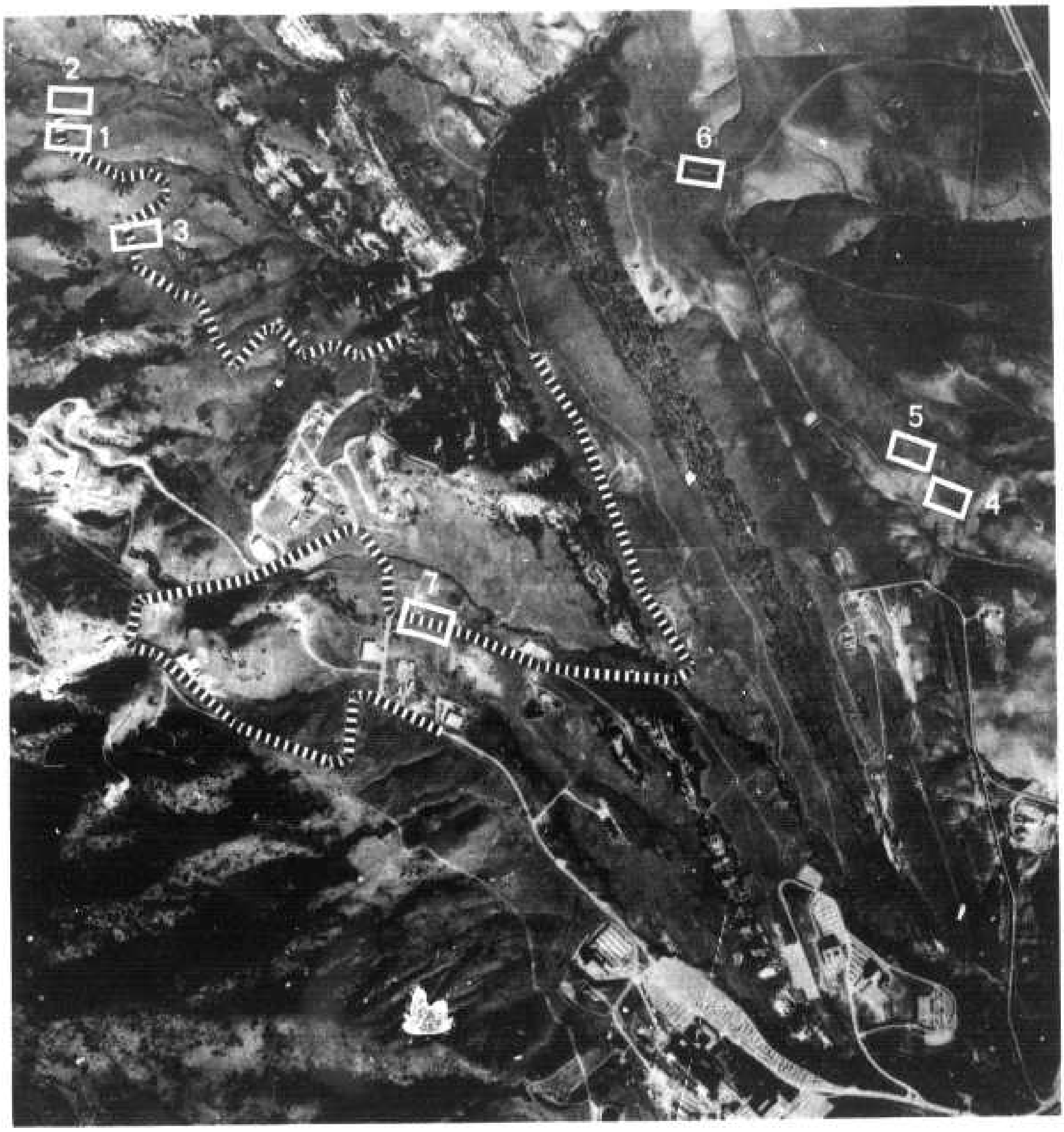

Figure 3-3. Measurement Test Sites July 1985

▮▮▮▮▮▮ Indicates Road Areas Traversed

☐ Indicates MSS Sites

A typical scene for MSS data is shown in Figures 3-4 and 3-5. This location was chosen near ETL Site #89 and was selected not only for solar aspect but for the diverse types of background components in the scene. Note the various vegetation types, dirt road with puddle of water, rocks, etc. The photographs were taken from the sensor platform. Note the shadow of the sensor and photographer in the foreground of Figure 3-5 which indicates the sun is directly behind the sensor thereby achieving a small bistatic angle between the sun, sensor, and target area.

3.3 September 1985 Measurements

A measurement scenario similar to that which occurred in July 1985 was planned for September 1985. The van deployed to the Denver site on schedule; however, after departure, it was learned that arrangements could not be made with the Denver Air National Guard for the loan of a mobile power unit. Many alternate sources were investigated but none could be arranged in a timely manner. Since the primary purpose of the measurements was for passive multispectral data, the MSS system was rewired at the Martin-Denver facility to operate from the van's auxiliary power unit and a 28 VDC power supply furnished by Martin.

Measurements were made at a total of ten different sites with a total of 42 data runs. See the data log in Appendix C. Figure 3-6 shows the Denver site overlay with the measurement sites indicated.

3.4 May 1986 Measurements

Prior to the May 1986 measurements, ERIM acquired a new van and reconfigured it with self-contained power units. All sensors were re-installed on a platform over the cab as in the original installation.

The emphasis during the May measurements was on specific calibration sequences laid out by Martin. Eight scenarios were programmed to provide animated collection of data simulating speeds over various roads, terrain, etc. See Table 3-1 for a listing of the scenarios. Site locations are indicated in Figure 3-7.

Figure 3-4. Photograph of Ground Scene Near ETL Site #89

Figure 3-5. ETL Measurement Site #89 with Calibration Panels

Figure 3-6. Measurement Test Sites September 1985

☐ Indicates MSS Sites

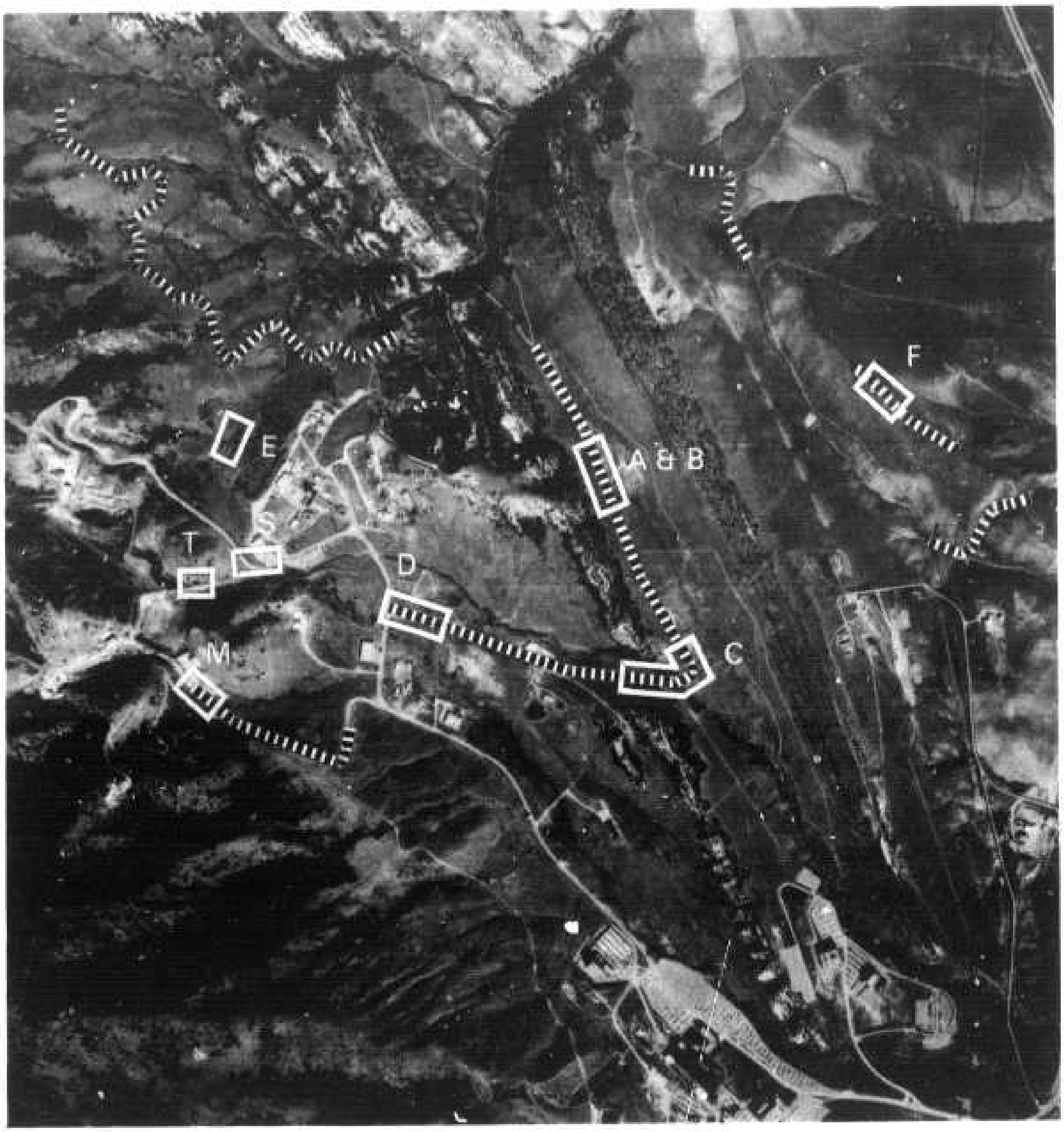

Figure 3-7. Measurement Test Sites — May 1986

▮▮▮▮▮▮ Indicates Road Areas Traversed

☐ Indicates Scenario and MSS Sites

Table 3-1
SCENARIOS FOR MAY 1986 MEASUREMENTS

	Site	Speed (KPH-simulated)	Data Interval (Meters)	Total Images
1 Asphalt road, no obstacles	A	10	1.39	20
2 Curving road	C	10	5.55	10
3 Intersection approach	D	10	5.55	10
4 Obstacle requiring maneuver	B	10	5.55	10
5 Obstacle requiring a stop	B	10	5.55	10
6 Multiple obstacles requiring maneuver	B	10	5.55	10
7 Dirt road (both straight and curved)	E	10	5.55	20
8 Straight path in open terrain	F	5	2.77	10

Prior to the measurement scenarios the depression angle of the 3-D sensor was set for a nominal 21.5 degrees; i.e., -6.5° to -36.5° below the horizon, and a series of calibration sequences were performed near a concrete revetment site where known ranges and angles could be measured. The MSS sensor was also operated at this site; however, measurements were made near noon local time and the sky was almost entirely overcast, hence, the MSS data were only useful in determining the sensor scanning geometry.

The scenarios were run only with the 3-D and TV sensors. Martin personnel had previously staked out all of the sites. After initial trial run the measurements procedures became routine. A plumb was attached to the front of the van and, with the aid of a guide assisting the van driver, the vehicle was positioned within an inch of the indicator on the roadway. The 3D sensor and tape recorder were run continuously throughout each scenario. Approximately 10 seconds of data were acquired at each location, the van was then advanced to the next position, the sensor line count was reinitiated, and the next 10 seconds of data recorded, etc, etc.

Additional continuous 3D data was acquired over the ALV road networks throughout the Martin test site. One of the staked sites, Site F, was located in open terrain; continuous 3D data were acquired enroute to this site and in the immediate vicinity. See Figure 3-7. The procedure at Site F was also somewhat different; although it was near noon when the measurements were made, MSS data were also acquired at each location at this site and, instead of running the tape recording systems continuously as at the other scenario locations, new runs were made at each position.

A series of MSS data was acquired on 30 May during the early morning hours. Specific sites were chosen considering solar aspect and types of terrain. Unfortunately, the van could not enter the dirt road complex at Martin where previous MSS data had been acquired due to extreme muddy conditions. On 1 June, when the van could enter the area, the sky was overcast which prohibited acquisition of meaningful data.

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SECTION 4
DATA FORMAT

The image sensors on ERIM's instrumented van may all be operated simultaneously, however, there was no attempt made to achieve pixel by pixel registration of the data from any combination of the sensors. The two channels, ie, range and reflectance, from the 3D sensor are in registration, as are the 12 channels from the MS sensor. All three sensors are nominally boresighted with one another.

Sensor data are all recorded on magnetic tape in the van. Three separate recorders are used. The color TV is recorded directly on 3/4-inch video cassettes with 60-minute time duration. Data from the 3D and MS sensors are recorded separately on 14-track digital tape recording systems. Transfer of the data to computer tapes is accomplished at ERIM's Ann Arbor facility.

4.1 3D Sensor Data

Single frame formatted data for the 3D sensor are provided as "labeled tapes" and are mounted as "VAX tape, 1600 bpi" and "VAX/VMS copy utility". These tapes will have range and reflectance files which are labeled by either gn####.img* or fn####.img* and a run number, n=run number. The range and reflectance files each contain 64 "active" scan lines. The "back scan" lines are usually deleted when reformatting the data; however, the May 1986 tapes which were distributed contain an additional 16 lines of "backscan" starting with the first scan line at the top of the frame.

The range data contain header pixel values on each scan line, so that these scan lines are 30+256 pixels in length. See Section 4.2. The reflectance files contain 256 pixels with no header. In both cases, each tape record contains 512 bytes of packed data (i.e., no pad zeros).

*#### = 4 digit, image number with leading zeros.

There is also a text file, On.txt, which contains file descriptions which include:

N = run number and

test files describing the run.

The image files are organized as follows:

first record (top of image) to last record (bottom of image)

first pixel(left side of image) to last pixel(right side of image)

4.2 Scan Line Header Format

The scan line header format implemented on the tape recording system is described below. The data sequence, starting immediately after the non-roll-stabilized line sync, is listed in Table 4-1; see notes below.

(1) The recorded header data is identical for each track, and is recorded immediately preceding each scan line. The scan-line data is different for each track.

(2) Line Count (Byte numbers 0 and 1 in Table 4-1) is a 16-bit binary number, and will be displayed on the control panel as a four-place hexadecimal number.

(3) Time since photo is the time, in milliseconds, since the last time the metric camera shutter was tripped. It also is a 16-bit binary number.

(4) The status byte is recorded as Byte No.4 in the table. It shows the radar polarization and the 3D scanner ambiguity interval for the scan line data which follows the header in which the byte occurs. It also shows the crystal clock frequency for the recording system. The coding is as follows. (The MSB bit 7 occurs first)

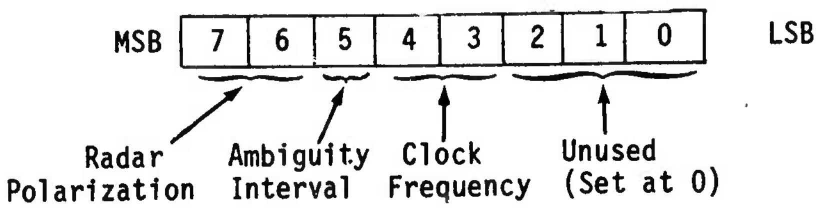

Table 4-1
HEADER FORMAT

Byte	Data
0	Line Count M.S. Byte [2*]
1	Line Count L.S. Byte
2	Time Since Photo M.S. Byte [3]
3	Time Since Photo L.S. Byte
4	Status Byte[4]
5	Channel Number (only last 3 bits)
6	Laser Power (#1 Laser)[5]
7	Laser Power (#2 Laser)
8	A_x M.S. Byte [6]
9	A_x L.S. Bye (only 1st 2 bits)
10	A_y M.S. Byte
11	A_y L.S. Byte (only 1st 2 bits)
12	A_z M.S. Byte
13	A_z L.S. Byte (only 1st 2 bits)
14	Roll M.S. Byte (01------) where dashes are M.S. 6 bits[7]
15	Roll L.S. Byte (8 bits)
16	Pitch M.S. Byte (10------) where dashes are M.S. 6 bits
17	Pitch L.S. Byte (8 bits)
18	Heading M.S. Byte (11------) where dashes are M.S. 6 bits
19	Heading L.S. Byte (8 bits)
20	Radar Altitude M.S. Byte[8]
21	Radar Altitude L.S. Byte
22	Wander Angle M.S.Byte (2 BCD,hundreds and tens of degrees)
23	Wander Angle L.S.Byte (2 BCD, units and tenths of degrees)
24	Run I.D. (2 BCD)
25	Month (2 BCD)
26	Day (2 BCD)
27	Year (2 BCD)

28 No. of pixels per scan line per channel M.S. Byte (2 BCD, thousands and hundreds)

29 No. of pixels per scan line per channel L.S. Byte (2 BCD, tens and hundreds)

30 First Byte of Line Scan Data

4.3 MSS Data

The multispectral system scans horizontally ±50° with an instantaneous field of view (IFOV) and sampling rate such that 803 pixels are generated across the field of view (FOV). See Figure 4-1. The vertical scan is manually controlled by an operator switching the nodding mirror beneath the sensor. The vertical scan is at a constant angular rate and is set to provide proportionate horizontal and vertical scale, ie, the correct perspective of the imaged scene. Vertical scans are typically made ±45° with respect to the horizon, resulting in approximately 800-900 scan lines for a given frame. When reformatting the data, each scene was viewed on a display and only 512 lines of data selected with the top of the frame positioned such that a portion of the sky was contained in each image. the horizontal FOV was also reduced by extracting only 512 pixels from the center of the image. The resulting frame, therefore, consists of 512 scan lines with 512 pixels per line. Note, the near-field image, i.e., that portion of the terrain close to the van, is out of focus as the MS sensor is designed for airborne use and has the focus preset to infinity. See Figure 4-2 for a typical MSS image at the Denver ALV test site. Note the shadow of the van and defocused image in the foreground.

The MSS data are reformatted to computer tape without header information. File names are identified xmulti##.img, where x is the run number and ## is the channel number within the frame.

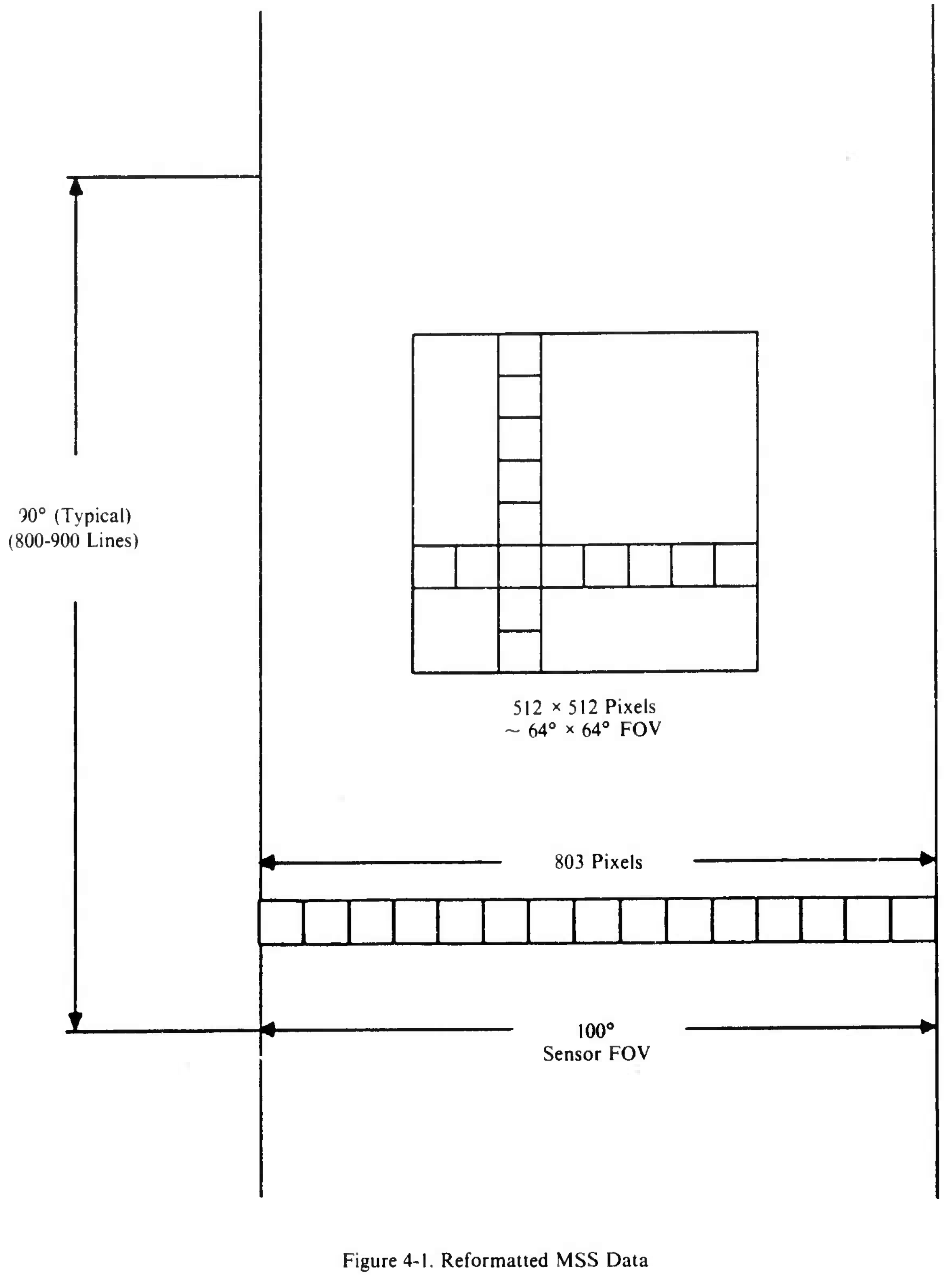

Figure 4-1. Reformatted MSS Data

Figure 4-2. Multi Spectral Image, July 1985, Run 12, Band 2

4.4 INS Data

The following is a brief discussion on the use of the INS data recorded in the header information for the 3D sensor. Header bytes 8 thru 29 (except 20 and 11) are relevant to the task of navigation. See Table 4-1.

The framing rate for the 3D sensor is 2 frames/second, the scan rate is 6.25 msec/scan; and the duty cycle is 80% (i.e. there are 64 active scan lines and 16 back-scan lines).

The translation data Ax, Ay, Az are represented in 10 bit unsigned binary format corresponding to +/- acceleration due to gravity g.

```
0 units --------------> 2**10 units
 -g     --------------> +g
```

The coordinate system is based on an 'intertial space' in which the x-axis is offset from true north (determined by earth rate) by the 'wander angle'. The wander angle varies from run to run; but, is fixed throughout any particular run (it is set manually by thumb-wheels after the INS system self-calibrates and settles, i.e., approximately 15 minutes after it is switched on).

Roll is recorded in 14-bit unsigned binary format corresponding to 0 to 360 degrees, where 0 and 360 degrees represents 'no roll'. Angles are measured clockwise looking in the direction forward travel of the vehicle.

```
0 units ----  --------> 2**14 units
0 degrees-------------> 360 degrees
```

Roll is therefore in units of 1/2**14 of 360 degrees with:

0 degrees (no roll) as 0 or 2**14 units

180 degrees as 2**13 units. (roll over time!!)

There is a wrap around at 2**13 s.t. 2**13 to 2**14 should be viewed as a counterclockwise roll.

i.e. Roll = (measured roll) - 2**14

```
               2**14 or 0 units
                      |
3*(2**12) units - - - + - - - 2**12 units
                      |
                  2**13 units
```

Pitch is recorded in 14-bit unsigned binary format corresponding to 0 to 360 degrees, where 0 and 360 degrees represents 'no pitch' and in the direction of forward travel. Angles are measured counterclockwise with angles increasing as the nose of the vehicle pitches up.

0 units ----------------> 2**14 units
0 degrees----------------> 360 degrees.

Pitch is therefore in units of 1/2**14 of 360 degrees

0 degrees as 0 or 2**14 units (in the horizontal tangent plane)
180 degrees as 2**13 units (Note, vehicle is on its back!)
Angles above 2**13 should be interpreted as 'pitch down'.
i.e. Pitch = (measured pitch) - 2**14

```
                 2**12 units
                     :
2**13 units - - - - -+- - - - - -0 or 2**14 units (vehicle heading)
                     :
                 3*(2**12) units
```

Heading is recorded in 14-bit unsigned binary format corresponding to 0 to 360 degrees.

0 units ----------------> 2**14 units
0 degrees----------------> 360 degree

Heading is therefore in units of 1/2**14 of 360 degrees and is measured clockwise from the x-axis of the inertial platform or space.

true heading = measured heading + wander angle

The coordinate system with the wander angle and heading is shown in Figure 4-3.

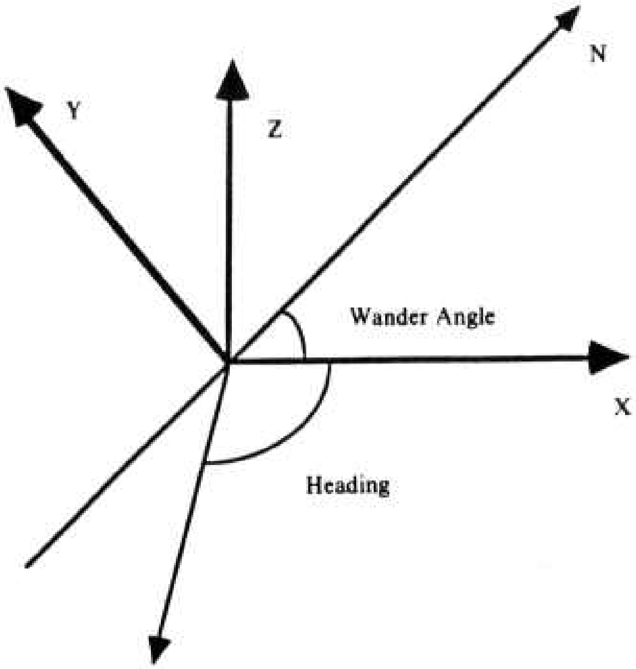

Figure 4-3. Coordinate System for Navigation

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SECTION 5
DISTRIBUTION OF DATA BASE

This report has summarized the image-sensor data collection program conducted by ERIM for the DARPA ALV program. Extensive amounts of data were recorded during all four measurement periods. Only a very small percentage of the data has been transferred to computer tapes to date. Primary emphasis was placed on the July 1985 and May 1986 data since these periods had all sensors operating.

5.1 Data Anomolies

The sensor data were not without anomolies. For example, Channel 9 of the MSS was inoperable during the July 85 mission. This mission was also the first time ERIM's ALV 3D sensor was used and the reflectance data channel had a defect which resulted in the "most significant bit" folding over into the remaining bit levels, rendering the reflectance data ambiguous. The sensors were operated over very rough terrain at the Martin Denver site; on occasion sensor vibration caused dropouts or digital count levels to increase from a few pixels to an entire scan line. During both the July 1985 and May 1986 collection periods, the 3D sensor had heat build-up problems causing thermal cut-outs within the sensor. This latter problem does not manifest itself in the data, however, as data was not recorded during these periods.

5.2 Computer Tape Distribution

Duplicate video tapes, i.e., color TV VCR cassettes of all the runs were delivered to Martin Marietta after each mission. In general, these tapes were used to select areas or scenes which were desired for reformatting sensor data to computer tape.

There were few requests from the ALV community for data from the September 1984 mission as the 3D sensor was somewhat unique to the ASV program. Computer tapes of specific areas were provided to OSU, Martin, Hughes and SRI, however.

Selected areas of the July 1985 data were reformatted and duplicated in twelve copies for the ALV community. A single composite TV tape was duplicated as were one 3D data tape and 2 MS data tapes. Table 5-1 lists the details of the July 1985 data which was distributed. A list of the recipients of the data is provided in Table 5-2.

As indicated in Section 3.3, only the multispectral sensor was operated during the September 1985 mission. None of this data has been reviewed or reformatted to date.

The May 1986 measurement period provided the most extensive and potentially useful set of data. Complete duplicates of the video cassettes have been sent to Martin and SRI. Selected segments of both the 3D and MSS data as indicated in Table 5-3, have also been sent to Martin Marietta.

Table 5-1

SUMMARY OF JULY 1985 DATA DISSEMINATED

TV DATA (1 Tape)

Composite Tape from July 85 Data Containing:
6 Runs, 11 Sec, 3D Road Data *
5 Runs, 11 Sec, 3D Cross Country Data *
13 Scenes, 10 Sec, MS Data **
1 Run, 24 Min, 3D Road Data (Solar Lab to ALV Lab)
1 Run, 20 Min, 3D Cross Country
1 Run, 10 Min, 3D Cross Country (Reverse)

*3D DATA (1-CCT, 1600 BPI)

11 Segments @ 11 Sec./Segment
22 Frames/Segment (ie, 2 Frames/Second)
2 Images/Scene (Range and Reflectance)
484 Image Files Total
64 Scan Lines/Image
256 Pixels/Scan Line

**MS DATA (2-CCT, 1600 BPI) 12 SCENES ONLY

6 Scenes/CCT
14 Images/Scene (12 MS, Range, Reflectance)
84 Image Files/CCT
168 Image Files Total
512 Scan Lines/Image
512 Pixels/Scan Line

Table 5-2
ALV DATA RECIPIENTS

Stanford Research Institute (SRI)
333 Ravenswood Avenue
Menlo Park, CA 94025
Attn: Dr. Steve Barnard (Robert Bolles) 415-859-4620

AI & DS
201 San Antonio Circle
Mountain View, CA 94040
Attn: Dr. Ted Linden 415-941-3912

Hughes
Artificial Intelligence Center
23901 Calabasas Road
Calabasas, CA 91302
Attn: Dr. David Tseng (Karin Olin) 818-702-5276

Carnegie-Mellon University (CMU)
Schenely Park
Pittsburgh, PA 15213
Attn: Dr. Chuck Thorpe 412-578-3612

University of Maryland
Center of Automation Research
College Park, MD 20742
Attn: Prof. Larry Davis 301-454-4526

Martin Marietta
Denver Aerospace
P.O. Box 179
Denver, CO 80201
Attn: James Allison, MS T0572, 303-977-5461

Massachusetts Institute of Technology
545 Technology Square
Cambridge, MA 02139
Attn: Jim Little 617-253-5230

Honeywell Systems and Research Center
2600 Ridgway Parkway NE
Minneapolis, MN 55413
Attn: Durga P. Panda 612-378-5058

University of Southern California
Towell Hall, Rm. 232
Los Angeles, CA 90089-0273
Attn: Dr. Nevatia 213-743-5516

University of Massachusetts
Amherst, MA 01003
Attn: Prof. Ed Riseman 413-545-2746

University of Rochester
Rochester, NY 14627
Attn: Prof. Chris Brown 716-275-7852

U.S. Army
Engineering Topographical Laboratories (ETL)
Ft. Belvoir, VA 22060-5546
Attn: Ms. Rose Holecheck 202-355-2679

Table 5-3
MAY 1986 REFORMATTED DATA

3D Sensor (selected segments only)

5/28 Runs #1, 2

5/29 Runs #1-7

5/30 Runs #1-15, 17, 18, 22

MSS Sensor

5/29 Runs 1, 2, 12, 13

5/30 Runs 1, 2, 4, 5, 7, 11

APPENDIX A

DATA COLLECTION LOG

SEPTEMBER 1984

APPENDIX A

DATA LOG
ASV SENSOR - DENVER DATA COLLECTION

9/25/84 Weather: Overcast

RUN	TIME	SITE	COMMENTS
1	14:34	Road Site	Middle of Road, 7 KTS
2	---	Road Site	Middle of Road
3	15:08	Road Site	Weaving, 8-9 KTS
4	15:21	Road Site	Weaving, 5-6 KTS
5	15:35	Road Site	Right Side of Road
6	15:44	Road Site	Middle and Right Side

9/26/84 Weather: Overcast

RUN	TIME	SITE	COMMENTS
1	10:40	Road Site	Aborted due to bad VCR
2	11:12	Road Site	
3	11:48	Road Site	Reverse of Run #2 (Cars both directions)
4	15:33	Road Site	6 KTS
5	16:45	Road Site	
6	17:30	Road Site	

9/27/84 Weather: Partly Cloudy

RUN	TIME	SITE	COMMENTS
1	16:12	Road Site	Changed to wide angle lens on TV
2	17:13	Dirt Road	
3	17:40	Dirt Road	

APPENDIX B

DATA COLLECTION LOG

JULY 1985

APPENDIX B

DATA LOG 7/2/85
ALV-MMS DENVER DATA COLLECTION

Litton Wander Angle	:	3328
ALV HDDT	:	ALV Tape #2
Video	:	Video Tape #2
Audio	:	Audio Tape #1, Side B
		Audio Tape #2, Side A

ALV Run Number	Time	Video Tape Count	Comments
1	11:09:30 -11:33:20	013	Run #1 originated at Solar Lab (013A2), destination ALV drive entrance (462A2) Changed Audio Tape: Audio Tape #2, Side A
2	11:51:20 -12:14:00	462 -737	Run #2 originated at ALV Building at road junction (462B2), destination Solar Lab (737B2)
3	12:23:00 -12:35:35	737	Run #3 originated at Solar Lab (737C2), destination road junction (857C2) Run #3 was the optional Martin Marietta data taken with the ALV set at 16° to 46° depression angle.

DATA LOG 7/2/85

ALV-MMS DENVER DATA COLLECTION (con't)

Litton Wander Angle	:	2080
ALV HDDT	:	ALV Tape #3
Video	:	Video Tape #3
Audio	:	Audio Tape #2, Side B

ALV Run Number	Time	Video Tape Count	Comments
1	16:08:00 -16:28:15	012 -406	Recorder start 16:07:45 Cross-country road ALV Data
2	16:43:00 -16:56:00	406 -587	Recorder start 16:42:50 Emergency stop -- Power unit oscillation Run #1 originated at entrance road junction (012A3), destination road junction past ETL area (406A3) Run #2 was the reverse of Run #1, (406B3)-(597B3)

DATA LOG 7/3/85

ALV-MMS DENVER DATA COLLECTION

No Litton Data	:	
ALV HDDT	:	ALV Tape #4
MMS HDDT	:	MMS Tape #1
Video	:	Video Tape #4
Audio	:	Audio Tape #3, Side A

Run MMS	Number ALV	Time (Reset)	Video Tape Count (Start)	Location	Position	
1	1	6:54:20	013	1	1	ETL Site #89
2	2	6:58:00	024	1	1	
3	3	7:03:25	035	1	2	
4	4	7:06:50	047	1	3	
5	5	7:16:40	059	1	4	
6	6	7:2120	069	1	5	
7	7	7:53:10	084	2	1	Dirt Road Site
8	8	7:55:10	094	2	1	
9	9	7:58:40	100	2	2	
10	10	8:02:10	110	2	3	
11	11	8:05:30	120	2	4	
12	12	8:07:40	129	2	5	
13	13	8:10:10	138	2	6	
14	14	8:28:00	148	3	1	Curve/Hill Site
15	15	8:30:50	157	3	2	
16	16	8:33:00	166	3	3	
17	17	8:35:40	175	3	4	
18	18	8:38:00	183	3	5	

Note: Recorders were started 10-15 seconds before reset time.

DATA LOG 7/4/85

ALV-MMS DENVER DATA COLLECTION

No Litton Data	:	
ALV HDDT	:	ALV Tape #4
MMS HDDT	:	MMS Tape #1
Video	:	Video Tape #4
Audio	:	Audio Tape #4, Side A

Run MMS	Number ALV	Time (Reset)	Video Tape Count (Start)	Location	Position
19	19	6:42:00	192	4	1 w/Panels Grass Site
20	20	6:46:30	201	4	1 w/Panels Grass Site
21	21	6:52:50	210	4	2 w/o Panels Grass Site
22	22	6:55:50	218	4	3
23	23	6:57:20	226	4	3
24	24	6:59:30	234	4	3
25	25	7:03:10	242	4	4
26	26	7:21:20	250	5	1 Grass Site
27	27	7:26:30	258	5	2
28	28	7:28:50	266	5	3
29	29	7:31:40	273	5	4
30	30	7:34:00	281	5	5
31	31	8:09:20	288	6	1 Road Site (Dirt)
32	32	8:11:30	296	6	2
33	33	8:15:00	303	6	3
34	34	8:17:20	310	6	4
35	35	8:18:50	317	6	4
36	36	8:21:20	325	6	5
37	37	9:32:30	332	7	1 Asphalt Road by Contractor Area
38	38	9:35:00	339	7	2
39	39	9:38:00	346	7	3
40	40	9:40:20	352	7	4
41	41	9:42:20	359	7	5
42	42	9:44:50	366	7	6

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APPENDIX C

DATA COLLECTION LOG

SEPTEMBER 1985

APPENDIX C

DATA LOG 9/25/85

MSS DENVER DATA COLLECTION

Run No.	Time	Site	Position/Comments
1	08:33:40	A	1 Hill Top Site
2	08:38:17	A	1 w/Cal Panels
3	*09:02 (15:23:25)	B	1 Access Road (Right)
4	*09:05 (15:26:15)	B	1 w/Cal Panels
5	09:36:15	C	1 ETL Site #89
6	09:41:00	C	2
7	09:43:50	C	3
8	09:48:00	C	4
9	09:51:45	C	5
10	09:56:10	C	6
11	09:59:45	C	7
12	10:03:53	C	8
13	10:07:30	C	8 w/Cal Panels
14	10:17:38	C	9 Looking Up Road
15	10:26:45	D	1 Roadside (LOC#2, 7/85)
16	10:58:05	E	1 Snowberry by Ravine
17	14:43:17	F	1 Road Site (CC)
18	14:46:05	F	2
19	14:49:10	F	3
20	14:51:50	F	4
21	14:54:40	F	5
22	15:04:30	F	5 w/Cal Panels
23	15:42:35	G	1 Rock Site w/Cal Panels
24	15:43:60	G	1
25	15:47:55	G	2
26	15:51:10	G	3
27	15:55:15	G	4

*Time Counter Reset Incorrectly

DATA LOG 9/26/85

MSS DENVER DATA COLLECTION

Run No.	Time	Site	Position/Comments
28	08:47:42	H	1 Road Site (Tar) w/Panel
29	08:55:00	H	1
30	08:58:12	H	2
31	09:00:25	H	3
32	09:02:30	H	4
33	09:06:10	H	5
34	09:10:55	I	1 New Tar Road Site
35	09:14:05	I	2 w/Panel
36	09:17:40	I	3
37	09:21:05	I	4
38	09:23:15	I	5
39	09:36:50	K	1 Road Site (Propane Tank)
40	09:39:00	K	2
41	09:40:30	K	3
42	09:41:55	K	4

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APPENDIX D

DATA COLLECTION LOG

MAY 1986

APPENDIX D

DATA LOG 5/28/86
ALV-MSS DENVER DATA COLLECTION

RUN	TIME START	TIME STOP	3D/MS	LOCATION/POSITION	REMARKS
1	14:59:40	15:06:24	Y/N	Road enroute from "T" to Solar Lab	
2	15:08:03	15:16:34	Y/N	Reverse of Run #1	#1 & #3 panels at road side, 23 ft. apart

DATA LOG 5/29/86
ALV-MSS DENVER DATA COLLECTION

WEATHER: OVERCAST

RUN	TIME START	TIME STOP	3D/MS	LOCATION/SCENE	REMARKS
1	14:00:00	14:00:48	Y/Y	Cal Site/1	4-squares on frame
2	14:05:24	14:06:20	Y/Y	2	Frame moved back, (No TV)
3	14:20:10	14:22:26	Y/N	3	INS Activated; Moving, Reversed 10 ft. - Forward 7 ft.
4	14:23:46	14:24:43	Y/Y	4	Reversed 3 ft., (No TV)
5	14:36:22	14:36:57	Y/Y	5	Cal Panels,L-R:3-1-2 w/ color chart
6	14:38:17	14:38:45	Y/Y	6	Same as 5 w/o color chart
7	14:49:36	14:50:49	Y/N	7	Moving towards blocks at 45° angle
8	14:58:06	14:59:40	Y/N	ALV Road Site M	
9	15:02:49	15:04:42	Y/N	ALV Road Site M	Reverse Route
10	15:09:38	15:10:09	Y/N	MSS Site M/1	MSS Inoperative
11	15:11:00	15:11:30	Y/Y	MSS Site M/1	Repeat #10
12	15:15:06	15:15:37	Y/Y	MSS Site M/2	~ 100 ft. down hill
13	15:18:35	15:19:02	Y/Y	MSS Site M/3	~ 200 ft. down hill
4	15:36:55	15:39:56	Y/N	ALV Road Site C	Curve enroute Solar Lab
15	15:44:43	15:46:57	Y/N	ALV Road Site C	Reverse Run #14, Mud on Road

DATA LOG 5/30/86
ALV-MSS DENVER DATA COLLECTION

WEATHER: CLEAR

RUN	TIME START	TIME STOP	3D/MS	LOCATION/SCENE	REMARKS
1	06:34:03	06:34:30	Y/Y	ALV Road Site S	With #1 & #3 Panels
2	06:35:32	06:36:00	Y/Y	ALV Road Site S	#1 Panel Shadowed
3	06:37:52	06:38:17	Y/Y	ALV Road Site S	w/o Panels
4	06:45:55	06:46:35	Y/Y	ALV Road Site T	
5	07:17:32	07:18:00	Y/Y	ALV Road Curve Site C/1	#1 & #3 Panels
6	07:18:50	07:19:14	Y/Y	ALV Road Curve Site C/1	w/o Panels
7	07:22:47	07:23:11	Y/Y	ALV Road Curve Site C/2	Forward ~ 100 ft.
8	07:37:34	07:38:02	Y/Y	MSS Site M/1	#3 Panel
9	07:38:32	07:38:57	Y/Y	MSS Site M/1	w/o Panel
10	07:47:19	07:47:44	Y/Y	MSS Site M/2	Back ~ 100 ft.
11	08:02:02	08:02:41	Y/Y	MSS Site M/1A	Repeat Run #8 w/panel #3
12	08:03:13	08:03:37	Y/Y	MSS Site M/1A	Repeat Run #8 w/o panel #3
13	10:13:54	10:24:12	Y/N	MM Site A	Multiple Stops w/line count resets
14	10:33:46	10:41:29	Y/N	MM Site C	Multiple Stops Curve Site
15	12:37:27	12:44:30	Y/N	MM Site D	Multiple Stops Road "T" site
16	13:06:42	13:08:44	Y/N	MM Site B	Multiple Stops w/obstacle

DATA LOG 5/30/86-con't
ALV-MSS DENVER DATA COLLECTION

RUN	TIME START	TIME STOP	3D/MS	LOCATION/SCENE	REMARKS
17	13:12:05	13:17:13	Y/N	MM Site B	Repeat #16
18	13:28:00	13:32:52	Y/N	MM Site B	With #1 & #2 Panels
19	13:34:38	13:35:48	Y/N	MM Site B	Moving to Panels
20	13:47:46	13:53:14	Y/N	MM Site B	Staggered Panels
21	14:05:30	14:06:17	Y/N	MM Site B	Moving through staggered panels
22	14:10:38	14:10:38	Y/N	ALV Road Curve Site C	Clean Wet road w/car

DATA LOG 5/31/86
ALV-MSS DENVER DATA COLLECTION

WEATHER: CLEAR

RUN	TIME START	TIME STOP	3D/MS	LOCATION/SCENE	REMARKS
1	11:55:13	11:59:01	Y/N	CC Pasture	Enroute to MM Site F
2	12:03:06	12:07:28	Y/N	Pasture w/Flags(Site F)	Enroute to and over flagged site
3	12:31:34	12:32:07	Y/Y	Flagged Site F	Stop & Go, Forward and Reverse Wheel Markings
13	12:46:30	12:46:56	Y/Y	Flagged Site F	Panels at end #1R, #3L
14	12:52:59	12:55:53	Y/N	Pasture Site	Return route
15	12:57:22	13:01:07	Y/N	Pasture Site	Return continued
16	13:13:17	13:16:57	Y/N	Dirt Road @ Pasture Site	Start at Power Lines
17	16:20:29	16:30:14	Y/N	MM Flag Site E	Stop & Go
18*	16:37:23	16:40:40	Y/N	CC Dirt Road	Start at Back Country "T", continuous over Site E
19*	16:57:46	17:00:01	Y/N	CC Dirt Road	Continue Run 18

*Intermittent power problems

DATA LOG 6/1/86
ALV-MSS DENVER DATA COLLECTION

WEATHER: PARTLY CLOUDY-OVERCAST

RUN	TIME START	TIME STOP	3D/MS	LOCATION/SCENE	REMARKS
1	06:22:43	06:35:16	Y/N	CC Dirt Road	Start at Back Country "T", TV in/out shadow
2	06:41:18	06:51:04	Y/N	CC Dirt Road	Reverse of 1

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LIST OF REFERENCES

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2. Zuk, D.M., Dell'Eva, M.L., and Van Atta, P., "3D Sensor for Adaptive Suspension Vehicle", Report Number 164700-4-F, Environmental Research Institute of Michigan, Ann Arbor, Michigan, November 1984.

3. Rinker, J.N., etal, "Terrain Data Base - Air Photo Analysis, Martin Marietta ALV Test Site", U.S. Army Engineer Topographic Laboratories, Ft. Belvoir, Virginia, January 1986.